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COMPARISON OF THREE RULES OF THUMB
TO THE OPTIMAL SOLUTION IN INVESTIGATION THEORY
- WITH SAMPLE PROBLEMS

by

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ABSTRACT:

The investigation problem considered here is one in which there is an investigator in a region with several objects, all of which are attempting to cross a specific boundary of the region. The investigator is to investigate as many of the objects as possible before they cross the boundary. In this paper it is assumed that all objects are moving parallel to one another directly toward the boundary. The investigator has speed greater than the objects, and can change his course instantaneously.

Forty sample problems with 20 objects each were randomly generated and solved optimally using branch and bound methods previously developed by the authors. In the first twenty problems, all targets have the same speed. In the second set of twenty problems, the target speeds differ. Solutions for the same problems were obtained through application of three easily implemented "rules of thumb". The effectiveness of each rule of thumb is determined through comparison of results with the optimal solutions.

Prepared by:

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I Introduction and Problem Description

The authors are currently engaged in research in the area of "Investigation Theory" which deals with the problem of determining the optimal sequence in which an investigator should visit a number of moving targets in order to visit as many as possible before they reach some prescribed boundary. Numerous assumptions are possible about the motion of the targets, the motion of the investigator, and the nature of the investigation. We assume in this report that each of the targets moves in a plane with a constant speed directly toward some prescribed boundary. The single investigator moves with a speed greater than that of any target and is free to change his course instantaneously. Naturally, he always moves at his maximum speed. To investigate a target only requires that the positions of the investigator and the target coincide. No time is required for the investigation in this report, although that case can easily be handled. The only times involved are the sequence dependent travel times between targets and the known times at which the targets reach the boundary.

This report does not describe the method by which the optimal sequence is computed. That description can be found in [1]. The optimal sequences referred to here may not be unique.

II Rules of Thumb

The purpose of this report is to compare several "rules of thumb" which might actually be applied in a real investigation problem. Such rules are more easily implemented than the optimal solution technique, and it is desired to determine their effectiveness in such problems. Three rules are compared to the optimal.

1) S.T.P. - Shortest Time Path. This rule always directs the investigator to move next to that target which is closest in time to the investigator's current position providing that the investigator can reach that target before it reaches the boundary.

2) S.D.P. - Shortest Distance Path. This rule directs the investigator to move next to the target closest in distance to the investigator's current position providing that the target can be reached before it crosses the boundary.

3) C.T.B. - Closest To Boundary. Using this rule the investigator procedes next to the target closest to the boundary providing it can be reached before it crosses the boundary.

The sequences generated by these rules are compared to the optimal sequences by considering forty problems each of which has

twenty objects whose initial positions are generated randomly from a uniform distribution. The object nearest the boundary is considered to be the investigator. The other 19 are the targets.

The region considered is 10 units wide and 10 units deep. In the first set of problems, in section III, the investigator has a speed of 25 units per unit time, and the targets have a speed of 15 units per unit time. In the second set of problems, section IV, the targets have speeds drawn from a uniform distribution between 10 and 20 units per unit time.

A square region was used because this appears to present the most difficult problem for a fixed number of objects. A wide, shallow region will allow the investigator to capture only those few targets relatively near his position, most of the others being out of reach even if he goes toward them immediately. A narrow, deep region will present little difficulty since the investigator will normally be able to capture a large fraction of the targets with any reasonable sequence.

III Same Target Speeds

a) The results from this set of twenty problems are summarized in Table 3-0 which shows for each problem the number of targets captured in the optimal solution and with each of the three rules. For each problem the ratio of the number of targets captured using the rule to the number captured optimally is computed and these ratios are averaged.

PROBLEM	1	2	3	4	5	6	7	8	9	10	AVERAGE OF EFFECTIVENESS RATIOS
OPT	11	11	11	11	13	12	11	11	9	9	
S.T.P.	10	9	8	10	12	10	9	10	9	5	
S.D.P.	10	9	7	11	13	12	9	10	9	9	
C.T.B.	8	11	6	6	12	10	11	9	9	6	

PROBLEM	11	12	13	14	15	16	17	18	19	20	
OPT	11	9	12	10	12	14	10	9	9	10	1.00
S.T.P.	10	7	10	10	12	10	8	8	7	9	.85
S.D.P.	10	8	6	10	12	13	10	9	9	10	.92
C.T.B.	8	9	12	9	12	12	8	8	9	10	.87

OPT = Optimal
S.T.P. = Shortest TIME Path
S.D.P. = Shortest DISTANCE Path
C.T.B. = Closest to Border

Table 3-0: Summary of Results for 20 Sample Problems with All Targets having the Same Speed.

It can be seen from Table 3-0 that for these 20 problems the best of the three rules is S.D.P. The S.T.P. and C.T.B. rules appear to be less effective. The deficiency of the S.T.P. rule is that it has a tendancy to move the investigator outward from the boundary toward incoming targets, foregoing nearby targets which might

later be impossible to capture since they would have to be "run down" from behind. The C.T.B. rule suffers from the deficiency that it causes the investigator to make more movements parallel to the boundary than might otherwise be required. Time is thus wasted in back and forth motion.

Each of the rules is nearsighted and looks only one step ahead, but in view of the results presented here it would appear that if computer equipment is not available to compute optimal solutions, the S.D.P. rule should be applied. It is easier to apply than the S.T.P. rule since no relative motion calculations need to be made.

Closely related to the investigation problem being considered is the 1XN job-shop scheduling problem with sequence dependent set-up times in which the criteria used is minimization of the number of late jobs. This criteria renders useless all standard techniques developed to solve the job-shop problem through formulation as a traveling salesman problem.

When viewed in job-shop context, the C.T.B. rule represents the rule "process next the job nearest its due-date", and the S.T.P. rule the "nearest neighbor" rule, (or process next that job with the shortest processing time). The results contained in Table 3-0 indicate that there is no substantial difference between these two rules. The S.D.P. rule has no counterpart in the job-shop problem.

b) Data for Sample Problems - Same Speeds

Tables 3-1 to 3-20 present the data used in the 20 sample problems in which all targets had the same speed, 15 units per unit time.

The investigator's speed is 25 units per unit time. This data is included so that if other rules are later proposed they can readily be compared to the rules presented here.

Figure 1 provides a pictorial representation of the first problem just for illustration. It must be remembered that the targets are moving and the actual ground track of the investigator is not that shown in the figure.

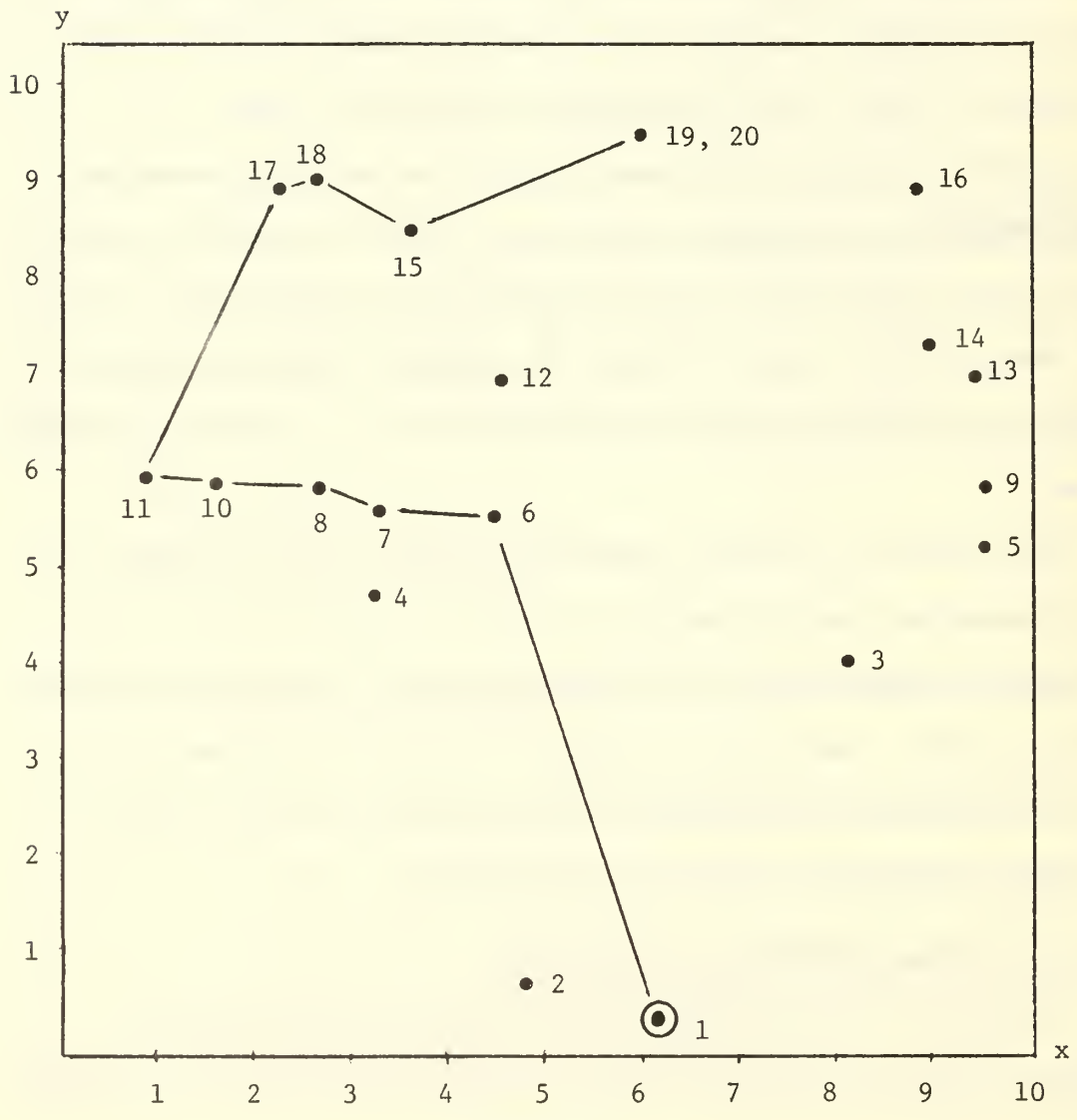

Figure 1

TABLES 3-1 to 3-20

PROBLEM 1

OBJECT	1	2	3	4	5	6	7	8	9	10
X=	6.04	4.76	8.05	3.24	9.50	4.67	3.17	2.58	9.51	1.77
Y=	0.33	0.76	4.18	4.82	5.26	5.64	5.72	5.89	5.92	5.96

OBJECT	11	12	13	14	15	16	17	18	19	20
X=	0.81	4.55	9.43	3.85	3.58	8.69	2.23	2.57	5.98	5.93
Y=	5.99	7.08	7.18	7.40	8.57	9.03	9.03	9.10	9.61	9.61

SOLUTION

OPT	1	6	7	8	10	11	17	18	15	19	20
STP	1	3	5	9	13	14	16	20	19	18	
SDP	1	3	5	9	13	14	16	20	19	18	
CTB	1	3	5	9	12	15	17	18			

PROBLEM 2

OBJECT	1	2	3	4	5	6	7	8	9	10
X=	9.98	9.06	5.40	4.95	2.66	9.85	1.04	3.73	4.96	6.41
Y=	0.05	0.82	1.52	1.79	1.90	2.43	3.62	4.26	5.31	5.86

OBJECT	11	12	13	14	15	16	17	18	19	20
X=	9.03	4.67	7.15	7.44	4.17	8.53	1.64	0.73	8.83	9.20
Y=	6.11	7.16	7.89	8.11	8.68	8.89	9.46	9.77	9.80	9.80

SOLUTION

OPT	1	2	6	9	10	12	13	14	16	19	20
STP	1	2	6	11	14	13	16	19	20		
SDP	1	2	6	11	14	13	16	19	20		
CTB	1	2	6	9	10	12	13	14	16	19	20

PROBLEM 3

OBJECT	1	2	3	4	5	6	7	8	9	10
X=	3.23	1.16	0.66	1.30	9.13	6.82	2.36	2.89	4.81	5.12
Y=	0.29	1.33	1.61	1.62	2.25	2.34	2.35	2.33	3.67	4.43

OBJECT	11	12	13	14	15	16	17	18	19	20
X=	7.82	3.13	2.15	9.75	1.04	5.76	9.93	1.55	1.59	1.18
Y=	4.63	5.19	5.34	5.47	5.54	6.32	6.36	6.49	8.03	9.26

SOLUTION

OPT	1	7	8	9	10	12	13	15	19	18	20
STP	1	8	7	12	13	18	19	20			
SDP	1	8	7	9	10	16	20				
CTB	1	2	3	10	16	20					

PROBLEM 4

OBJECT	1	2	3	4	5	6	7	8	9	10
X=	6.09	4.47	8.95	4.33	7.24	8.40	1.54	4.93	5.82	6.42
Y=	0.03	0.35	1.17	3.13	3.32	4.04	5.06	5.44	6.17	6.18

OBJECT	11	12	13	14	15	16	17	18	19	20
X=	7.79	9.53	3.96	6.68	3.81	1.21	0.63	2.10	4.97	9.23
Y=	6.35	6.70	5.94	7.04	7.77	8.61	8.38	9.10	9.73	9.89

SOLUTION

OPT	1	5	6	10	9	8	13	15	18	16	17
STP	1	5	6	11	14	10	9	13	15	19	
SDP	1	5	6	11	14	10	9	13	15	18	19
CTB	1	4	7	9	14	19					

PROBLEM 5

OBJECT	1	2	3	4	5	6	7	8	9	10
X=	6.66	1.30	2.58	4.40	8.02	9.45	6.03	2.77	8.09	7.66
Y=	1.39	1.43	2.42	2.80	3.62	3.75	4.28	4.35	4.43	5.15

OBJECT	11	12	13	14	15	16	17	18	19	20
X=	6.08	5.41	1.08	4.16	4.97	4.13	4.14	1.95	5.02	0.61
Y=	5.44	5.73	6.20	7.03	7.14	8.05	8.51	9.01	9.31	9.79

SOLUTION														
OPT	1	5	9	10	7	11	12	15	16	17	19	18	20	
STP	1	5	9	10	11	12	15	16	17	19	18	20		
SDP	1	5	9	10	11	12	15	14	16	17	19	18	20	
CTB	1	4	7	9	10	11	12	14	15	16	17	19		

PROBLEM 6

OBJECT	1	2	3	4	5	6	7	8	9	10
X=	8.08	1.79	8.75	8.86	1.17	7.12	6.91	6.60	9.40	3.09
Y=	0.05	0.56	0.88	1.19	1.21	2.38	3.74	4.27	4.68	5.75

OBJECT	11	12	13	14	15	16	17	18	19	20
X=	2.79	1.68	3.35	5.59	7.80	9.08	6.28	7.41	0.34	0.42
Y=	5.89	6.03	6.07	6.64	7.02	7.57	8.78	8.82	8.89	9.10

SOLUTION														
OPT	1	3	4	6	7	8	10	11	13	14	18	17		
STP	1	3	4	6	7	8	14	17	20	16				
SDP	1	3	4	6	7	8	14	15	16	13	17	20		
CTB	1	3	4	6	7	8	9	14	17	18				

PROBLEM 7

OBJECT	1	2	3	4	5	6	7	8	9	10
X=	8.84	4.97	1.59	8.20	0.99	0.31	9.42	8.62	8.52	8.74
Y=	0.35	0.40	0.62	1.02	1.80	1.91	2.03	3.17	3.51	3.72

OBJECT	11	12	13	14	15	16	17	18	19	20
X=	1.06	4.38	0.21	1.44	9.89	3.96	2.21	1.93	5.08	1.96
Y=	4.83	5.96	6.81	7.09	7.32	7.75	7.85	8.15	9.75	9.97

SOLUTION												
OPT	1	4	7	8	9	12	16	17	18	20	19	
STP	1	4	7	8	9	10	15	19	20			
SDP	1	4	7	8	9	10	15	16	19			
CTB	1	4	7	8	9	10	12	14	17	18	19	

PROBLEM 8

OBJECT	1	2	3	4	5	6	7	8	9	10
X=	2.03	6.89	5.83	1.86	8.37	6.69	1.69	2.02	4.11	3.53
Y=	0.71	1.14	1.59	1.92	2.25	3.16	3.33	3.40	3.74	5.41

OBJECT	11	12	13	14	15	16	17	18	19	20
X=	0.04	1.84	7.99	3.26	6.59	1.86	9.97	1.47	5.93	6.11
Y=	5.89	6.56	6.84	6.86	7.34	9.08	9.34	9.39	9.59	9.79

SOLUTION												
OPT	1	4	7	8	10	14	12	16	18	19	20	
STP	1	4	7	8	10	14	16	13	19	20		
SDP	1	4	7	8	9	10	14	12	16	18		
CTB	1	4	7	8	9	10	11	16	18			

PROBLEM 9

OBJECT	1	2	3	4	5	6	7	8	9	10
X=	7.28	1.86	7.18	1.51	3.23	7.84	4.51	9.27	4.69	6.20
Y=	1.18	1.36	1.59	1.87	1.97	2.25	2.53	2.63	3.54	3.67

OBJECT	11	12	13	14	15	16	17	18	19	20
X=	7.63	0.12	5.61	0.50	4.76	0.49	7.46	3.83	1.23	5.41
Y=	4.16	4.13	4.94	4.98	6.43	7.37	7.37	7.47	8.07	8.34

SOLUTION

OPT	1	3	6	8	11	13	17	20	18	
STP	1	3	6	11	13	17	20	18	19	
SDP	1	3	6	8	11	13	15	18	20	
CTB	1	3	6	8	10	13	15	17	20	

PROBLEM 10

OBJECT	1	2	3	4	5	6	7	8	9	10
X=	1.11	6.57	7.00	2.85	8.86	0.19	6.13	7.65	6.68	2.74
Y=	0.75	1.40	1.47	2.04	2.25	2.83	3.18	3.45	4.15	4.54

OBJECT	11	12	13	14	15	16	17	18	19	20
X=	5.58	9.62	4.39	9.28	0.11	7.49	7.81	7.49	7.48	1.16
Y=	4.76	4.82	5.16	5.58	6.32	6.43	6.69	9.46	9.34	9.98

SOLUTION

OPT	1	4	7	11	13	16	17	18	19	
STP	1	6	15	20	19					
SDP	1	4	10	13	11	16	17	18	19	
CTB	1	4	6	10	15	20				

PROBLEM 11

OBJECT	1	2	3	4	5	6	7	8	9	10
X=	5.90	3.96	6.60	5.51	3.52	1.40	1.48	2.97	3.56	7.44
Y=	0.79	2.33	2.46	2.92	3.33	4.06	4.66	4.77	5.29	5.31

OBJECT	11	12	13	14	15	16	17	18	19	20
X=	4.18	8.46	0.83	5.31	1.00	2.95	1.72	6.18	7.63	0.09
Y=	5.53	5.82	6.08	6.74	6.88	6.96	7.09	7.71	9.37	9.69

SOLUTION

OPY	1	3	4	5	8	9	11	16	17	15	20
STP	1	3	4	11	9	8	16	17	15	20	
SDP	1	3	4	5	8	9	11	14	18	19	
CTB	1	2	4	7	13	15	16	20			

PROBLEM 12

OBJECT	1	2	3	4	5	6	7	8	9	10
X=	1.91	3.60	0.58	4.35	9.49	7.51	9.29	6.08	9.48	5.41
Y=	0.00	0.08	0.11	0.63	1.15	1.17	1.31	2.59	3.19	3.42

OBJECT	11	12	13	14	15	16	17	18	19	20
X=	4.85	8.87	6.99	4.12	9.44	2.02	4.84	7.44	7.50	7.24
Y=	3.52	5.67	5.37	6.73	7.42	8.17	8.55	9.05	9.30	9.90

SOLUTION

OPT	1	10	11	13	14	17	19	18	20
STP	1	11	10	13	18	19	20		
SDP	1	11	10	13	15	18	19	20	
CTB	1	8	10	11	13	15	18	19	20

PROBLEM 13

OBJECT	1	2	3	4	5	6	7	8	9	10
X=	6.51	0.41	9.07	9.73	5.19	1.49	9.62	4.13	0.88	9.59
Y=	0.48	0.84	2.67	3.03	3.78	4.03	4.36	4.43	4.74	4.99

OBJECT	11	12	13	14	15	16	17	18	19	20
X=	5.51	5.48	0.54	2.89	4.36	0.37	2.66	9.62	1.64	0.93
Y=	5.51	5.74	6.62	6.62	7.08	8.38	9.08	9.08	9.15	9.31

SOLUTION													
OPT	1	3	4	7	10	11	12	14	15	17	19	20	
STP	1	5	8	11	12	15	17	19	20	16			
SDP	1	3	4	7	10	18							
CTB	1	3	4	7	10	11	12	14	15	17	19	20	

PROBLEM 14

OBJECT	1	2	3	4	5	6	7	8	9	10
X=	6.12	6.25	8.16	6.46	0.64	1.55	4.00	3.18	7.11	0.80
Y=	0.64	1.84	1.88	1.92	1.93	2.95	3.74	3.84	4.36	4.54

OBJECT	11	12	13	14	15	16	17	18	19	20
X=	8.56	6.55	9.23	0.38	7.28	0.47	6.53	4.38	2.10	9.31
Y=	4.72	4.96	5.04	5.45	5.55	6.69	6.74	7.28	7.31	9.39

SOLUTION											
OPT	1	2	4	9	12	15	11	13	17	20	
STP	1	2	4	9	12	15	17	18	19	20	
SDP	1	2	4	3	9	12	15	17	18	19	
CTB	1	2	3	9	11	13	15	17	20		

PROBLEM 15

OBJECT	1	2	3	4	5	6	7	8	9	10
X=	9.41	9.53	3.12	0.77	7.77	9.45	9.38	6.34	2.07	6.42
Y=	0.18	0.58	0.84	1.78	2.07	3.74	4.31	4.70	5.32	5.80

OBJECT	11	12	13	14	15	16	17	18	19	20
X=	3.26	6.84	2.72	2.84	4.89	9.18	5.57	4.13	5.33	0.46
Y=	6.04	6.46	6.70	6.87	7.23	7.61	7.65	8.27	8.73	9.75

SOLUTION													
OPT	1	2	5	6	7	8	10	12	15	17	18	20	
STP	1	2	5	6	7	8	12	10	17	15	18	20	
SDP	1	2	5	6	7	8	10	12	17	18	18	20	
CTB	1	2	5	6	8	10	12	15	17	19	20		

PROBLEM 16

OBJECT	1	2	3	4	5	6	7	8	9	10
X=	4.91	4.28	4.38	5.19	4.58	5.83	0.55	7.74	8.54	9.12
Y=	0.64	0.91	0.93	1.39	2.10	2.98	5.21	5.37	5.75	6.05

OBJECT	11	12	13	14	15	16	17	18	19	20
X=	7.51	4.73	7.42	5.30	7.42	7.48	0.70	0.87	7.35	2.38
Y=	6.20	6.26	6.40	7.18	7.52	7.81	8.50	8.61	9.04	9.95

SOLUTION														
OPT	1	2	3	4	5	6	8	13	11	10	14	15	16	19
STP	1	2	3	5	6	10	14	19	16	15				
SDP	1	2	3	4	5	6	8	11	13	15	16	19	20	
CTB	1	2	3	4	5	6	8	9	10	14	16	19		

PROBLEM 17

OBJECT	1	2	3	4	5	6	7	8	9	10
X=	3.92	2.68	0.65	0.17	8.74	7.28	8.71	6.14	3.70	4.63
Y=	0.41	0.55	0.78	1.47	1.71	1.75	2.14	2.16	2.21	2.53

OBJECT	11	12	13	14	15	16	17	18	19	20
X=	6.46	4.89	5.72	4.11	9.47	0.99	1.47	7.39	1.24	4.98
Y=	2.58	3.86	3.96	4.28	4.95	5.94	7.11	7.95	9.13	9.93

SOLUTION										
OPT	1	9	10	12	13	14	16	17	19	20
STP	1	9	10	12	14	13	18	20		
SDP	1	9	10	12	13	14	16	17	19	20
CTB	1	8	10	12	13	17	18	20		

PROBLEM 18

OBJECT	1	2	3	4	5	6	7	8	9	10
X=	9.52	9.50	8.30	5.92	3.64	3.05	5.36	6.69	9.26	7.30
Y=	0.05	0.67	0.98	1.19	1.64	2.78	3.07	3.40	4.03	4.12

OBJECT	11	12	13	14	15	16	17	18	19	20
X=	4.74	8.06	1.73	9.07	4.32	2.10	6.89	5.54	0.95	9.35
Y=	4.39	5.17	5.20	5.71	5.85	8.28	8.36	8.56	9.64	9.78

SOLUTION										
OPT	1	3	8	10	9	12	18	17	20	
STP	1	2	9	14	12	17	18	20		
SDP	1	2	9	12	14	17	18	16	19	
CTB	1	2	7	10	12	14	17	18		

PROBLEM 19

OBJECT	1	2	3	4	5	6	7	8	9	10
X=	6.23	7.34	9.11	7.52	4.76	7.88	5.81	1.40	2.14	3.03
Y=	0.75	0.98	1.01	1.02	1.38	1.64	1.78	2.31	3.67	4.02

OBJECT	11	12	13	14	15	16	17	18	19	20
X=	8.71	9.67	1.19	5.50	7.84	1.52	2.63	9.81	3.94	6.91
Y=	4.60	5.42	5.62	5.63	6.62	7.61	7.74	8.18	9.31	9.68

SOLUTION										
OPT	1	7	9	10	13	16	17	19	20	
STP	1	7	14	15	18	20	19			
SDP	1	7	10	9	13	16	17	19	20	
CTB	1	2	4	6	10	13	16	17	19	

PROBLEM 20

OBJECT	1	2	3	4	5	6	7	8	9	10
X=	4.09	7.03	5.74	7.26	2.44	0.11	1.49	2.14	7.64	4.59
Y=	0.50	0.56	0.63	0.73	2.48	2.88	3.96	4.18	4.25	4.32

OBJECT	11	12	13	14	15	16	17	18	19	20
X=	8.12	1.31	9.08	4.77	2.94	8.05	7.66	2.44	2.47	3.90
Y=	4.49	5.52	6.46	6.67	6.97	7.19	7.32	8.87	8.96	9.70

SOLUTION										
OPT	1	5	8	7	12	14	15	18	19	20
STP	1	5	8	7	12	15	18	19	20	
SDP	1	5	8	7	12	15	17	18	19	20
CTB	1	5	6	7	8	12	15	18	19	20

IV Different Target Speeds

a) The results from this set of 20 problems are summarized in Table 4-0.

PROBLEM	1	2	3	4	5	6	7	8	9	10	AVERAGE OF EFFECTIVENESS RATIOS
OPT	13	11	12	10	10	10	10	12	13	12	
S.T.P.	10	8	8	10	10	8	10	9	11	10	
S.D.P.	9	10	12	10	10	9	10	9	11	11	
C.T.B.	11	11	5	9	9	9	9	11	11	11	

PROBLEM	11	12	13	14	15	16	17	18	19	20	
OPT	12	12	10	12	11	11	10	11	11	16	1.00
S.T.P.	10	11	5	7	9	8	7	9	9	14	.78
S.D.P.	11	11	8	11	9	9	9	11	10	15	.89
C.T.B.	11	12	7	10	10	10	10	6	11	15	.86

OPT = Optimal
S.T.P. = Shortest TIME Path
S.D.P. = Shortest DISTANCE Path
C.T.B. = Closest to Border

Table 4-0: Summary of Results for 20 Sample Problems with Different Target Speeds.

The results from these 20 problems with different target speeds tend to substantiate the results given previously, namely, that the S.D.P. rule is more effective than the S.T.P. or C.T.B. rules.

The data for these problems is presented in tables 4-1 through 4-20.

TABLES 4-1 to 4-20

PROBLEM 1

OBJECT	1	2	3	4	5	6	7	8	9	10
X=	6.92	2.57	6.57	3.85	1.14	0.29	2.27	1.80	5.95	2.67
Y=	0.57	0.85	0.95	1.16	1.60	3.32	3.65	5.10	5.21	6.09
S=	25.0	12.1	11.5	10.2	18.7	19.8	11.0	14.7	12.2	16.7

OBJECT	11	12	13	14	15	16	17	18	19	20
X=	3.58	5.53	1.83	6.17	4.92	9.01	2.96	7.06	7.75	7.75
Y=	7.17	7.26	7.35	7.54	7.78	7.95	8.42	9.34	9.74	9.98
S=	12.7	13.3	11.3	15.8	19.4	12.7	11.6	16.0	14.3	14.7

SOLUTION														
OPT	1	3	7	8	10	15	9	14	12	18	16	19	20	
STP	1	3	9	14	12	18	19	20	16	17				
SDP	1	3	9	14	12	15	11	17	13					
CTB	1	3	7	8	10	9	14	12	11	13	17			

PROBLEM 2

OBJECT	1	2	3	4	5	6	7	8	9	10
X=	0.88	7.04	9.88	7.46	8.70	6.70	1.93	7.44	5.88	1.14
Y=	0.59	0.69	0.85	0.93	1.30	1.60	2.05	2.07	3.52	3.80
S=	25.0	13.8	15.3	14.0	10.2	19.5	13.5	12.6	17.7	14.6

OBJECT	11	12	13	14	15	16	17	18	19	20
X=	1.07	3.10	2.81	3.66	7.07	1.10	2.55	0.86	2.94	8.97
Y=	4.13	5.66	5.78	6.84	7.02	7.20	7.76	8.47	9.04	9.88
S=	13.7	16.1	19.3	12.1	19.5	19.7	16.9	10.4	16.1	18.5

SOLUTION												
OPT	1	7	10	11	12	13	16	17	14	19	18	
STP	1	7	10	11	16	17	19	18				
SDP	1	7	10	11	13	12	17	14	19	18		
CTB	1	7	10	11	13	12	16	17	14	19	18	

PROBLEM 3

OBJECT	1	2	3	4	5	6	7	8	9	10
X=	3.92	2.68	0.65	0.17	8.74	7.28	8.71	6.14	3.70	4.63
Y=	0.41	0.55	0.78	1.47	1.71	1.73	2.14	2.16	2.21	2.53
S=	25.0	12.5	17.8	10.9	11.3	17.8	10.0	13.1	17.6	15.5

OBJECT	11	12	13	14	15	16	17	18	19	20
X=	6.46	4.89	5.72	4.11	9.47	0.99	1.47	7.39	1.24	4.98
Y=	2.58	3.86	3.96	4.28	4.95	5.94	7.11	7.95	9.13	9.93
S=	18.5	19.0	10.4	12.4	15.8	11.4	12.6	10.4	19.6	13.3

SOLUTION												
OPT	1	9	10	12	13	14	16	19	17	20	18	
STP	1	9	10	12	14	13	18	20				
SDP	1	9	10	12	13	14	16	19	17	20	18	
CTB	1	7	15	17	20							

PROBLEM 4

OBJECT	1	2	3	4	5	6	7	8	9	10
X=	9.52	9.50	8.30	5.92	3.64	3.05	5.38	6.69	9.26	7.30
Y=	0.05	0.67	0.98	1.19	1.64	2.78	3.07	3.40	4.03	4.12
S=	25.0	12.7	17.2	19.2	12.6	15.4	19.0	10.0	19.0	13.0

OBJECT	11	12	13	14	15	16	17	18	19	20
X=	4.74	8.06	1.73	9.07	4.32	2.10	6.89	5.54	0.95	9.85
Y=	4.39	5.17	5.20	5.71	5.88	8.28	8.36	8.56	9.64	9.78
S=	19.8	12.0	13.6	13.0	12.1	10.7	17.1	19.1	10.1	11.1

SOLUTION

OPT	1	3	9	10	8	17	18	15	16	19
STP	1	2	9	14	12	17	18	15	16	19
SDP	1	2	9	10	8	12	14	17	20	19
CTB	1	2	8	10	12	14	15	16	19	

PROBLEM 5

OBJECT	1	2	3	4	5	6	7	8	9	10
X=	6.23	7.34	9.11	7.52	4.76	7.88	5.81	1.40	2.14	3.03
Y=	0.75	0.98	1.01	1.02	1.38	1.64	1.78	2.31	3.67	4.02
S=	25.0	13.2	10.4	12.9	12.2	11.6	18.8	18.6	13.6	18.7

OBJECT	11	12	13	14	15	16	17	18	19	20
X=	8.71	9.67	1.19	5.50	7.84	1.52	2.63	9.81	3.94	6.91
Y=	4.60	5.42	5.62	5.63	6.62	7.61	7.74	8.18	9.31	9.68
S=	14.7	16.5	16.3	18.1	12.2	17.2	15.3	16.1	12.6	13.6

SOLUTION

OPT	1	4	2	6	12	11	15	18	20	19
STP	1	7	5	10	9	13	16	17	19	20
SDP	1	7	5	10	9	13	16	17	19	20
CTB	1	2	4	6	11	14	15	20	19	

PROBLEM 6

OBJECT	1	2	3	4	5	6	7	8	9	10
X=	0.10	9.25	8.55	1.31	4.68	8.67	2.17	5.02	6.08	1.24
Y=	0.08	0.22	2.96	3.33	3.70	3.87	4.11	4.63	5.21	5.65
S=	25.0	15.3	11.6	12.4	15.6	10.2	15.1	15.2	14.2	16.7

OBJECT	11	12	13	14	15	16	17	18	19	20
X=	9.58	6.76	3.40	4.74	4.04	7.64	2.47	7.39	9.26	7.12
Y=	5.70	6.06	6.07	6.48	6.80	6.85	7.15	7.61	8.87	9.20
S=	12.9	18.2	15.1	14.7	12.1	14.4	15.7	19.2	11.0	19.8

SOLUTION

OPT	1	5	8	12	9	18	16	20	15	19
STP	1	4	7	10	17	15	14	19		
SDP	1	4	7	10	17	13	14	15	19	
CTB	1	4	7	8	12	9	14	15	19	

PROBLEM 7

OBJECT	1	2	3	4	5	6	7	8	9	10
X=	4.09	7.03	5.74	7.26	2.44	0.11	1.49	2.14	7.64	4.59
Y=	0.50	0.56	0.63	0.73	2.48	2.88	3.96	4.18	4.25	4.32
S=	25.0	14.0	12.2	18.2	17.8	13.0	19.8	15.0	15.3	19.6

OBJECT	11	12	13	14	15	16	17	18	19	20
X=	8.12	1.31	9.08	4.77	2.94	8.05	7.66	2.44	2.47	3.90
Y=	4.49	5.52	6.46	6.67	6.97	7.19	7.32	8.87	8.96	9.70
S=	10.9	16.9	14.1	19.6	15.9	10.4	18.6	19.4	16.9	12.5

SOLUTION

OPT	1	5	7	6	8	12	15	18	19	20	
STP	1	5	7	8	12	15	18	19	20	16	
SDP	1	5	7	8	12	15	18	19	20	16	
CTB	1	5	6	8	12	15	18	19	16		

PROBLEM 8

OBJECT	1	2	3	4	5	6	7	8	9	10
X=	6.04	4.76	8.05	3.24	9.50	4.67	3.17	2.58	9.51	1.77
Y=	0.33	0.76	4.18	4.82	5.26	5.64	5.72	5.89	5.92	5.96
S=	25.0	17.9	17.0	13.8	11.1	17.0	15.2	19.7	14.6	10.3

OBJECT	11	12	13	14	15	16	17	18	19	20
X=	0.81	4.55	9.43	8.85	3.58	8.69	2.23	2.57	5.98	5.98
Y=	5.99	7.08	7.18	7.40	8.57	9.03	9.03	9.10	9.61	9.61
S=	17.0	14.0	19.7	13.3	18.0	12.9	15.3	17.7	13.7	10.3

SOLUTION

OPT	1	6	4	8	7	12	15	18	10	17	19	20
STP	1	3	5	9	13	14	16	20	19			
SDP	1	3	5	9	13	14	16	19	20			
CTB	1	3	4	7	12	15	18	10	17	19	20	

PROBLEM 9

OBJECT	1	2	3	4	5	6	7	8	9	10
X=	8.08	1.79	8.75	8.86	1.17	7.12	6.91	6.60	9.40	3.09
Y=	0.05	0.56	0.88	1.19	1.21	2.38	3.74	4.27	4.68	5.75
S=	25.0	10.9	12.4	10.7	18.4	13.8	14.8	14.1	17.3	15.7

OBJECT	11	12	13	14	15	16	17	18	19	20
X=	2.79	1.68	3.35	5.59	7.80	9.08	6.28	7.41	0.84	5.42
Y=	5.89	6.03	6.07	6.64	7.02	7.57	8.78	8.82	8.89	9.10
S=	19.2	10.7	15.7	16.5	10.4	14.8	10.0	13.8	19.1	15.0

SOLUTION

OPT	1	3	4	6	7	8	10	13	12	20	18	15	17
STP	1	3	4	6	7	8	14	20	17	18	15		
SDP	1	3	4	6	7	8	14	13	12	20	17		
CTB	1	3	4	6	7	9	16	15	20	18	17		

PROBLEM 10

OBJECT	1	2	3	4	5	6	7	8	9	10
X=	8.84	4.97	1.59	8.20	0.99	0.31	9.42	8.62	8.52	8.74
Y=	0.35	0.40	0.62	1.02	1.80	1.91	2.03	3.17	3.51	3.72
S=	25.0	19.6	15.5	19.6	14.6	18.7	15.6	15.8	19.0	10.8

OBJECT	11	12	13	14	15	16	17	18	19	20
X=	1.06	4.38	0.21	1.44	9.89	3.96	2.21	1.93	5.08	1.96
Y=	4.83	5.96	6.81	7.09	7.32	7.75	7.85	8.15	9.76	9.94
S=	14.1	11.2	15.7	14.5	19.6	10.6	16.2	18.1	12.2	10.0

SOLUTION

OPT	1	4	8	9	10	12	18	17	14	16	19	20
STP	1	4	7	8	9	10	15	19	16	20		
SDP	1	4	7	8	9	10	15	12	16	19	20	
CTB	1	4	7	8	9	10	12	14	16	19	20	

PROBLEM 11

OBJECT	1	2	3	4	5	6	7	8	9	10
X=	2.03	6.89	5.83	1.86	8.37	6.69	1.69	2.02	4.11	3.53
Y=	0.71	1.14	1.59	1.92	2.25	3.16	3.33	3.40	3.74	5.41
S=	25.0	16.4	16.0	12.3	15.4	14.6	10.2	13.1	10.3	17.3

OBJECT	11	12	13	14	15	16	17	18	19	20
X=	0.04	1.84	7.99	3.26	6.59	1.86	9.97	1.47	5.93	6.11
Y=	5.89	6.56	6.84	6.86	7.34	9.08	9.34	9.39	9.59	9.79
S=	19.1	13.5	12.4	18.1	16.7	14.3	11.9	13.3	10.2	17.7

SOLUTION

OPT	1	4	7	8	9	10	14	12	16	18	19	17
STP	1	4	8	7	11	12	16	18	19	17		
SDP	1	4	8	7	10	9	14	12	16	18	19	
CTB	1	4	8	7	9	10	14	12	20	18	19	

PROBLEM 12

OBJECT	1	2	3	4	5	6	7	8	9	10
X=	7.28	1.86	7.18	1.51	3.23	7.84	4.51	9.27	4.69	6.20
Y=	1.18	1.36	1.59	1.87	1.97	2.25	2.53	2.63	3.54	3.67
S=	25.0	14.9	17.3	17.6	14.3	17.0	12.9	11.9	18.1	12.8

OBJECT	11	12	13	14	15	16	17	18	19	20
X=	7.63	0.12	6.61	0.50	4.76	0.49	7.46	3.83	1.23	5.41
Y=	4.16	4.13	4.94	4.98	6.43	7.37	7.37	7.47	8.07	8.34
S=	15.6	18.1	17.5	13.3	15.5	10.9	16.7	16.4	10.1	17.3

SOLUTION

OPT	1	3	6	9	7	10	13	15	18	20	16	19
STP	1	3	6	11	13	10	15	18	20	19	16	
SDP	1	3	6	8	11	13	10	15	18	20	19	
CTB	1	3	6	7	9	10	13	15	18	20	16	19

PROBLEM 13

OBJECT	1	2	3	4	5	6	7	8	9	10
X=	1.11	6.57	7.00	2.85	8.86	0.19	6.13	7.65	6.68	2.74
Y=	0.75	1.40	1.47	2.04	2.25	2.83	3.18	3.45	4.15	4.54
S=	25.0	14.9	13.3	17.9	14.7	12.7	16.9	10.1	17.6	12.9

OBJECT	11	12	13	14	15	16	17	18	19	20
X=	5.58	9.62	4.39	9.28	0.11	7.49	7.81	7.40	7.48	1.16
Y=	4.76	4.82	5.16	5.58	6.32	6.43	6.65	8.46	9.34	9.98
S=	16.9	17.3	18.3	19.8	12.6	17.3	12.2	15.5	10.7	10.3

SOLUTION										
OPT	1	4	13	11	8	16	17	18	19	20
STP	1	6	15	20	19					
SDP	1	4	10	13	17	18	19	20		
CTB	1	4	6	10	15	19	20			

PROBLEM 14

OBJECT	1	2	3	4	5	6	7	8	9	10
X=	5.90	3.96	6.60	5.51	3.52	1.40	1.48	2.97	3.56	7.44
Y=	0.79	2.33	2.46	2.92	3.33	4.06	4.66	4.77	5.29	5.31
S=	25.0	19.0	17.2	18.8	16.6	14.3	10.9	12.0	12.7	13.9

OBJECT	11	12	13	14	15	16	17	18	19	20
X=	4.18	8.46	0.83	5.31	1.00	2.95	1.72	6.18	7.63	0.09
Y=	5.53	5.82	6.08	6.74	6.88	6.96	7.09	7.71	9.37	9.89
S=	15.6	12.8	10.6	19.8	18.9	15.9	10.0	15.1	14.7	18.1

SOLUTION											
OPT	1	2	5	11	9	8	15	7	16	13	20	17
STP	1	3	4	14	18	19	17					
SDP	1	3	4	5	8	9	11	16	13	20	17	
CTB	1	2	4	8	11	9	16	13	20	17		

PROBLEM 15

OBJECT	1	2	3	4	5	6	7	8	9	10
X=	7.73	4.53	4.43	4.65	3.35	6.86	4.26	3.49	9.93	6.05
Y=	0.65	0.75	1.54	2.39	2.66	2.73	2.92	4.13	4.16	4.51
S=	25.0	10.5	11.5	14.3	13.3	12.2	10.9	11.4	15.9	14.1

OBJECT	11	12	13	14	15	16	17	18	19	20
X=	1.54	5.95	3.46	5.97	6.64	1.65	5.94	2.05	7.93	2.00
Y=	4.83	4.90	5.83	6.72	6.86	6.93	7.20	9.14	9.52	9.87
S=	10.5	14.0	19.6	11.2	18.3	19.1	12.0	12.6	18.5	18.6

SOLUTION											
OPT	1	4	5	13	8	16	11	20	17	14	18
STP	1	6	10	12	15	14	17	19	18		
SDP	1	6	10	12	15	14	17	19	18		
CTB	1	4	5	7	10	12	15	14	19	17	

PROBLEM 16

OBJECT	1	2	3	4	5	6	7	8	9	10
X=	6.51	0.41	9.07	9.73	5.19	1.49	9.62	4.13	0.88	9.59
Y=	0.48	0.84	2.67	3.03	3.78	4.03	4.36	4.43	4.74	4.99
S=	25.0	14.8	13.0	11.5	17.0	19.8	16.5	19.9	14.0	13.5

OBJECT	11	12	13	14	15	16	17	18	19	20
X=	5.51	5.48	0.54	2.89	4.36	0.37	2.66	9.62	1.64	0.98
Y=	5.51	5.74	6.62	6.62	7.08	8.38	9.08	9.08	9.15	9.31
S=	16.1	16.0	19.1	13.4	12.5	10.2	11.6	12.4	17.1	11.6

SOLUTION

OPT	1	5	8	9	13	19	14	15	17	20	16
STP	1	5	11	12	15	17	20	16			
SDP	1	3	4	7	10	18	17	20	16		
CTB	1	3	4	7	10	14	19	17	16	20	

PROBLEM 17

OBJECT	1	2	3	4	5	6	7	8	9	10
X=	1.91	3.60	0.58	4.35	9.49	7.51	9.29	6.08	9.48	5.41
Y=	0.00	0.08	0.11	0.63	1.15	1.17	1.31	2.59	3.19	3.42
S=	25.0	10.4	19.0	10.6	13.8	17.5	15.9	11.9	11.7	12.7

OBJECT	11	12	13	14	15	16	17	18	19	20
X=	4.85	8.87	6.99	4.12	9.44	2.02	4.84	7.44	7.50	7.24
Y=	3.52	5.67	6.37	6.73	7.42	8.17	8.55	9.05	9.30	9.90
S=	12.7	16.0	17.0	17.7	19.3	11.8	14.6	18.6	10.1	10.7

SOLUTION

OPT	1	11	10	13	15	18	17	16	19	20
STP	1	11	10	14	17	19	20			
SDP	1	11	10	13	18	17	16	19	20	
CTB	1	8	10	11	13	18	17	16	19	20

PROBLEM 18

OBJECT	1	2	3	4	5	6	7	8	9	10
X=	6.12	6.25	8.16	6.46	0.64	1.55	4.00	3.18	7.11	0.80
Y=	0.64	1.84	1.88	1.92	1.93	2.95	3.74	3.84	4.36	4.54
S=	25.0	10.0	11.7	10.4	10.5	13.4	19.1	11.8	14.1	11.1

OBJECT	11	12	13	14	15	16	17	18	19	20
X=	8.56	6.55	9.23	0.38	7.28	0.47	6.53	4.38	3.10	9.31
Y=	4.72	4.96	5.04	5.45	5.55	6.69	6.74	7.28	7.31	9.39
S=	18.6	14.9	16.4	14.6	14.0	15.3	12.4	10.4	15.3	16.9

SOLUTION

OPT	1	2	4	3	11	13	9	12	15	17	18
STP	1	2	4	9	12	15	17	18	19		
SDP	1	2	4	3	11	13	9	12	15	17	18
CTB	1	2	3	8	16	18					

PROBLEM 19

OBJECT	1	2	3	4	5	6	7	8	9	10
X=	6.09	9.41	9.53	3.12	0.77	7.77	9.45	9.38	8.34	2.07
Y=	0.03	0.18	0.58	0.84	1.78	2.07	3.74	4.31	4.70	5.32
S=	25.0	12.2	11.9	11.6	17.8	10.3	19.3	17.8	12.3	11.5

OBJECT	11	12	13	14	15	16	17	18	19	20
X=	6.42	3.26	6.84	2.72	2.84	4.89	9.18	5.57	4.13	8.33
Y=	5.80	6.04	6.46	6.70	6.87	7.23	7.61	7.65	8.27	8.73
S=	15.8	15.7	14.8	16.1	13.6	11.8	18.8	10.9	11.2	18.5

SOLUTION											
OPT	1	6	7	8	9	11	13	20	18	16	19
STP	1	6	8	9	17	20	18	19	16		
SDP	1	6	7	8	9	17	20	18	16	19	
CTB	1	6	7	8	9	11	13	20	16	18	19

PROBLEM 20

OBJECT	1	2	3	4	5	6	7	8	9	10
X=	4.91	4.28	4.38	5.19	4.58	4.83	0.55	7.74	8.54	6.12
Y=	0.64	0.91	0.93	1.39	2.10	2.98	5.21	5.37	5.75	6.05
S=	25.0	16.0	10.9	10.2	13.7	14.4	15.0	11.2	12.3	17.5

OBJECT	11	12	13	14	15	16	17	18	19	20
X=	7.51	4.73	7.42	5.30	7.42	7.48	0.70	0.87	7.35	2.38
Y=	6.20	6.26	6.40	7.18	7.52	7.81	8.50	8.81	9.04	9.95
S=	14.2	17.3	14.1	19.9	12.7	16.8	18.0	16.5	12.9	16.4

SOLUTION																
OPT	1	2	3	5	4	6	12	14	10	11	13	16	8	9	15	19
STP	1	3	2	5	4	6	10	14	12	13	16	8	15	19		
SDP	1	3	2	4	5	6	10	14	12	13	11	16	8	15	19	
CTB	1	2	3	4	5	6	10	12	14	11	13	9	8	15	19	

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13. ABSTRACT

The investigation problem considered here is one in which there is an investigator in a region with several objects, all of which are attempting to cross a specific boundary of the region. The investigator is to investigate as many of the objects as possible before they cross the boundary. In this paper it is assumed that all objects are moving parallel to one another directly toward the boundary. The investigator has speed greater than the objects, and can change his course instantaneously.

Forty sample problems with 20 objects each were randomly generated and solved optimally using branch and bound methods previously developed by the authors. In the first twenty problems, all targets have the same speed. In the second set of twenty problems, the target speeds differ. Solutions for the same problems were obtained through application of three easily implemented "rules of thumb". The effectiveness of each rule of thumb is determined through comparison of results with the optimal solutions.

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